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# Implementation of a drive-by monitoring system for transport infrastructure utilising GNSS

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**ABSTRACT:** Ageing and deterioration of infrastructure is a challenge facing transport authorities. In particular, there is a need for increased bridge monitoring in order to provide adequate maintenance, prioritise allocation of funds and guarantee acceptable levels of transport safety. Existing bridge structural health monitoring (SHM) techniques typically involve direct instrumentation of the bridge with sensors and equipment for the measurement of properties such as frequencies of vibration. These techniques are important as they can indicate the deterioration of the bridge condition. However, they can be labour intensive and expensive due to the requirement for on-site installations. In recent years, alternative low-cost indirect vibration-based SHM approaches have been proposed which utilise the dynamic response of a vehicle to carry out “drive-by” pavement and/or bridge monitoring. The vehicle is fitted with sensors on its axles thus reducing the need for on-site installations. This paper investigates the use of low-cost sensors incorporating global navigation satellite systems (GNSS) for implementation of the drive-by system in practice, via field trials with an instrumented vehicle. The potential of smartphone technology to be harnessed for drive by monitoring is established, while smartphone GNSS tracking applications are found to compare favourably in terms of accuracy, cost and ease of use to professional GNSS devices.

**KEY WORDS:** Acceleration; Bridge health monitoring; Drive-by; Global navigation satellite systems; Vehicle sensors.

## 1 INTRODUCTION

Bridges and pavements form an integral part of transport infrastructure worldwide. Over their lifetime, their condition will deteriorate due to factors such as environmental conditions, ageing and increased loading. In countries such as the U.S., Korea, Japan and across the E.U., a majority of bridge structures are now over 50 years old [1,2]. This leads to the requirement for increased monitoring and maintenance in order to prioritise allocation of funds and guarantee acceptable levels of transport safety, particularly where rehabilitation and life extension of bridge structures is necessary.

As traditional visual inspection methods for bridges can be highly variable, relying on visible signs of deterioration, bridge management systems (BMSs) are now more commonly integrating structural health monitoring (SHM) methods, involving direct instrumentation of bridge structures with sensors and data acquisition equipment, which target identification of damage from dynamic structural responses [3,4]. However, these methods can be labour intensive and expensive due to the requirement for on-site installations, which may require dense sensor networks. This has restricted widespread implementation of SHM for short and medium span bridges, which form the greatest proportion of bridges in service. Therefore, a more efficient alternative is required which can provide information about a bridge's condition.

Road pavement profile measurements are typically obtained using an inertial profilometer, which consists of a vehicle equipped with a height sensing device, such as a laser, which measures pavement elevations at regular intervals [5] with the effects of vehicle dynamics removed from the elevation measurements via accelerometer(s) and gyroscopes. The vehicle can travel at highway speeds and the method provides

accurate, high resolution profile measurements but a drawback is the expense associated with laser-based technology.

In recent years, alternative low-cost indirect vibration-based SHM approaches have been proposed by a number of researchers which utilise the dynamic response of a vehicle to carry out “drive-by” monitoring of bridges [6,7] and/or pavements [8]. The vehicle is fitted with sensors, such as accelerometers, on its axles to monitor vibration thus reducing the need for on-site installations and expensive laser-based sensors. However, these methods, summarised by Malekjafarian et al. [7], lack comprehensive experimental verification, with very few field trials reported in the literature. Based on existing research [7], three main challenges for drive-by monitoring have been identified as the road profile, the limited vehicle-bridge interaction (VBI) time (speed-dependent) and environmental effects, while also acknowledging practical issues such as ongoing traffic on a bridge and variation in speed of the instrumented vehicle.

Malekjafarian et al. [7] suggest that a potential solution to challenges related to limited VBI time and environmental effects is the use of instrumented vehicles that repeatedly pass over the same bridge, or pavement. This could be implemented by instrumenting a fleet of vehicles with sensors, e.g. public vehicles such as the public bus monitoring system investigated in Japan [9] which drive along the same route multiple times per day. An alternative lower-cost possibility is proposed in this paper; the use of smartphone technology and sensors. Due to the current prevalence of such technology, drive-by vehicle monitoring systems could potentially move beyond the limitation to unique instrumented vehicles, or localised instrumented vehicle fleets.

This paper is motivated by the aforementioned lack of field testing and thus investigates the implementation of such drive-by monitoring systems in practice via field trials. For this purpose, a two-axle vehicle is instrumented with accelerometers and global navigation satellite system (GNSS) receivers and is driven along predetermined routes in the Belfast road network. Aiming to take advantage of existing low-cost technologies, in addition to accelerometers designed for structural applications and a Leica GNSS receiver, smartphone accelerometers and global position tracking applications are also utilised during field trials. Measurements obtained from all sensors and receivers are compared in terms of accuracy, cost and ease of use in order to evaluate the effectiveness and feasibility of this monitoring system.

## 2 METHODOLOGY

For this field investigation, the instrumented vehicle was a Ford Transit van (Figure 1), weighing 1600 kg and fitted with accelerometers to measure vibration and GNSS receivers to record the vehicle position in the road network. A digital camera was also used to record video footage of each vehicle test run while the average vehicle speed during testing was 30 mph (48 km/h). The details of instrumentation and setup are outlined in the following sections.



Figure 1. Instrumented Vehicle.

### 2.1 Acceleration measurement setup

The overall setup of accelerometers in the vehicle is illustrated in Figure 2, consisting of 4 accelerometers measuring vertical vibration.

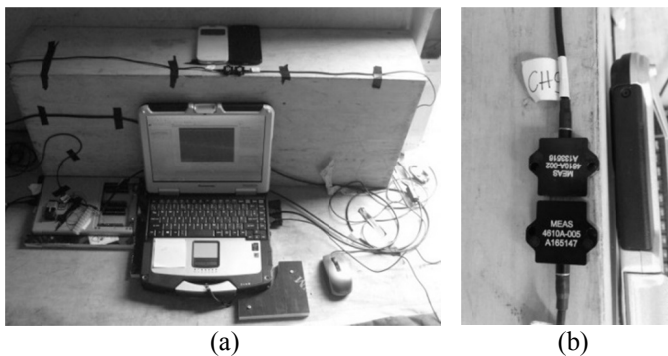


Figure 2. (a) Accelerometer instrumentation setup (b) uniaxial accelerometers.

#### 2.1.1 Wired accelerometers

Two wired uniaxial accelerometers were installed at the same location in the body of the vehicle, adhesively mounted over the left rear wheel. The installed accelerometers were ultra-low noise signal conditioned model 4610A-002 ( $\pm 2g$ ) and

4610A-005 ( $\pm 5g$ ) units by Measurement Specialties<sup>TM</sup>, shown in Figure 2(b), which provide low-pass filtered output. Excitation voltage was provided by a 9V battery during testing. Both  $\pm 2g$  and  $\pm 5g$  rated accelerometers were tested, for comparison with smartphone sensors and to ensure any large magnitude accelerations greater than 2g were recorded, respectively. The sampling frequency was 1000 Hz, which allows identification of any features with frequency components higher than 100 Hz, which would be undetected by the smartphone sensors.

#### 2.1.2 Smartphone sensors

The built in accelerometers of an LG Nexus 5 and a Samsung Galaxy S4 were used for vertical smartphone acceleration measurements; both devices were mounted over the left rear wheel with adhesive (Figure 2(a)). The LG Nexus 5, retailing at €290 approximately, contains a 6-axis MPU-6515 chip with integrated triaxial MEMS Gyroscope and triaxial MEMS accelerometer by InvenSense Inc., built into the device motherboard. The maximum measurement range during testing was  $\pm 19.61 \text{ m/s}^2$ , equivalent to  $\pm 2g$ , although this can be increased. As vehicle body and bridge vibration magnitudes are generally less than 2g, this range is suitable for bridge monitoring applications. The smartphone sampling frequency was set at a maximum of 200 Hz, which is also adequate for drive-by monitoring.

The Samsung S4, retailing at €220 approximately, uses a K330 triaxial accelerometer by STMicroelectronics. The maximum measurement range was  $\pm 19.61 \text{ m/s}^2$  ( $\pm 2g$ ), however, the maximum allowable sampling frequency on the Samsung S4 was 100 Hz during testing.

Accelerations were logged to the internal SD card of each device via the freely available Android smartphone application 'Vibration Alarm' by Mobile Tools. In terms of sampling consistency, it was observed that for around 3% of the total number of recorded samples, the sample interval varied by  $\pm 0.001 \text{ s}$  for both devices. Each accelerometer was powered by the internal lithium-ion batteries of their respective smartphones; the Nexus 5 by a 3.8 V, 2300 mAh battery and the S4 by a 3.8 V, 2600 mAh battery. An external 5200 mAh capacity portable power supply (costing €16) was also used as backup for the LG Nexus 5.

### 2.2 GNSS setup

In addition to recording acceleration measurements, accurately monitoring the position of the instrumented vehicle during its passage along a road network is valuable for a number of reasons. Firstly, if anomalous results or large peaks are observed in the acceleration record, they can be tagged with a location via GNSS tracking, allowing the engineer to rapidly pinpoint areas with potential pavement damage e.g. potholes or cracking. This type of approach has already been investigated for pothole detection in pavements using custom built devices combining accelerometers and GPS receivers [10], further incorporating video to enable screenshots of areas of interest [11], and smartphone applications integrating crowdsourcing [12]. Secondly, for bridge monitoring, it would enable identification of bridge crossings by the vehicle, allowing specific portions of the acceleration signal to be extracted and analysed using one of the many methods proposed in the literature [7].

### 2.2.1 Leica GNSS smart antenna

To serve as a reference for the vehicle position recorded by the Nexus 5 during testing, a Leica Geosystems Viva GS14 GNSS smart rover antenna was used to manually log the vehicle location coordinates to a removable SD card throughout testing, incorporating Network Real-Time Kinematic (RTK) corrections [13] obtained via mobile network. The antenna was mounted magnetically on the roof of the van and operated using a Leica Geosystems CS15 controller (see Figure 3). This system can achieve horizontal and vertical accuracies of 8 mm and 15 mm respectively for static measurements, although this is dependent upon various factors such as the number of satellites tracked, constellation geometry and observation time. Accuracy was expected to vary during testing, particularly in urban or wooded areas where satellite visibility or signal strength can be restricted, and due to the movement of the vehicle.

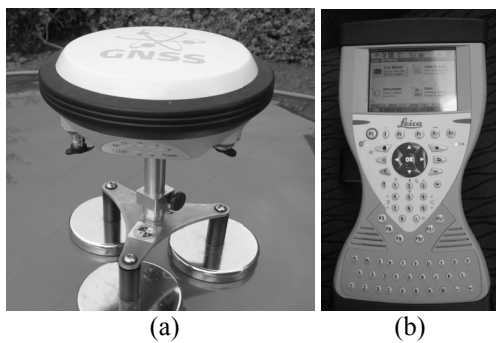


Figure 3. (a) Leica GS14 smart antenna (b) Leica CS15 controller.

### 2.2.2 Smartphone application

The vehicle location was also tracked during testing using a freely available Android smartphone application installed on the LG Nexus 5, namely 'GPSEssentials' by M. Schollmeyer [14]. This application utilises the smartphone's GPS transceiver (a Qualcomm WTR1605L) which also supports assisted GPS, to record the track followed by the vehicle. This particular application was selected as it provides average speed and elevation, allows the vehicle coordinates to be recorded and timestamped every second and can plot the resulting tracks in real time, or export them in .kml format for viewing on Google Earth.

### 2.3 Data acquisition

A National Instruments (NI) multifunction USB-6353 X-Series data acquisition (DAQ) device was used to log wired accelerometer measurements, at a sampling frequency of 1000 Hz, to a Panasonic Toughbook running NI Signal Express. Power to the DAQ device was provided by a 12V car battery placed in the rear of the vehicle, with the required output of 230Vac provided by an inverter. The total cost of this DAQ setup is approximately €7000.

### 2.4 Test Routes

Two test routes in the Belfast area of Northern Ireland were selected for testing, shown in Figures 9-11. Each route passes through urban and wooded areas, in addition to encompassing bridge crossings. Route 1 was 1.8 miles (2.9 km) long while

Route 2 was 12 miles (18 km) but included repeat bridge crossings over the M1 motorway. Both routes as tracked using GNSS systems are shown in Section 3.2.

## 3 IDENTIFICATION OF FEATURES

### 3.1 Acceleration Measurements

Figure 4 shows the full time history of acceleration measurements obtained from all accelerometers in the instrumented vehicle for route 1, while Figure 5 shows the corresponding spectra. It can be seen that despite the difference in sampling frequency, the smartphone acceleration time histories compare relatively well to the corresponding measurements from the wired 2g accelerometer, however, the Samsung S4 sensor (Figure 4(d)) is not as sensitive to the vibration magnitude as the Nexus 5, in many cases registering less than half the peak acceleration magnitude, which is influenced by its 100 Hz sampling frequency limitation. This is also reflected in the spectra (Figure 5). Although all sensors identify the dominant body bounce vibration mode of the vehicle at 2.3 Hz, the smartphone peak magnitude is 5 times less than that recorded by the wired sensor, indicating lower sensitivity; however, this magnitude difference is reflected across the whole spectrum.

Figure 4(a) shows the wired 5g accelerometer measurements for comparative purposes of positive accelerations; the sharp peaks at the beginning and end of the signals were used to confirm accurate synchronisation while the vehicle was motionless. During movement i.e. from 140 – 860 seconds, only four peaks exceeded +2g, marked in Figure 4 with arrows. However, the maximum peak magnitudes measured by the wired accelerometers were not obtained by the smartphones due to their range limit. The magnitudes and times for these four peak locations are given in Tables 1 and 2 respectively. From Table 1, it can be seen that in terms of smartphone measurements, the Nexus 5 accelerometer is more sensitive overall, reaching its range limit of  $19.24 \text{ m/s}^2$  consistently for peaks exceeding 2g, suggesting that it may be a more suitable device for drive-by monitoring purposes. Also, this accelerometer has the potential to have its dynamic range increased by the user. It should be noted however that this range limit is slightly less than specified ( $\pm 19.61 \text{ m/s}^2$ ), indicating that sensor calibration may be necessary.

From Table 2, the times corresponding to peaks in the acceleration signals with (left to right numbering) can be used to inspect video footage and timestamped vehicle location coordinates. Figure 6 shows video screenshots corresponding to each peak, highlighting that unique features are present at these locations. Peaks 1 and 2 were caused by speed ramps, while Peaks 3 and 4 were caused by manhole covers.

An example of the acceleration responses of the wired 2g uniaxial accelerometer and the Nexus 5 accelerometer for test route 2 are shown in Figure 8 for a west-east crossing of the skew-bridge (Figure 7) over the M1 motorway on Dunmurry Lane, which has a total length of approximately 38 m. This response was extracted based on the recorded position of the vehicle (Section 3.2) and inspection of video footage for test route 2. Similar responses were observed for repeated crossings. Firstly, it can be observed that the Nexus 5 accelerometer displays a noisier response, which is expected; the uniaxial accelerometer has been designed and constructed

for applications requiring low levels of output signal noise thus some higher frequency components have been removed from its response. However, both accelerometers display three periodic low frequency disturbances.

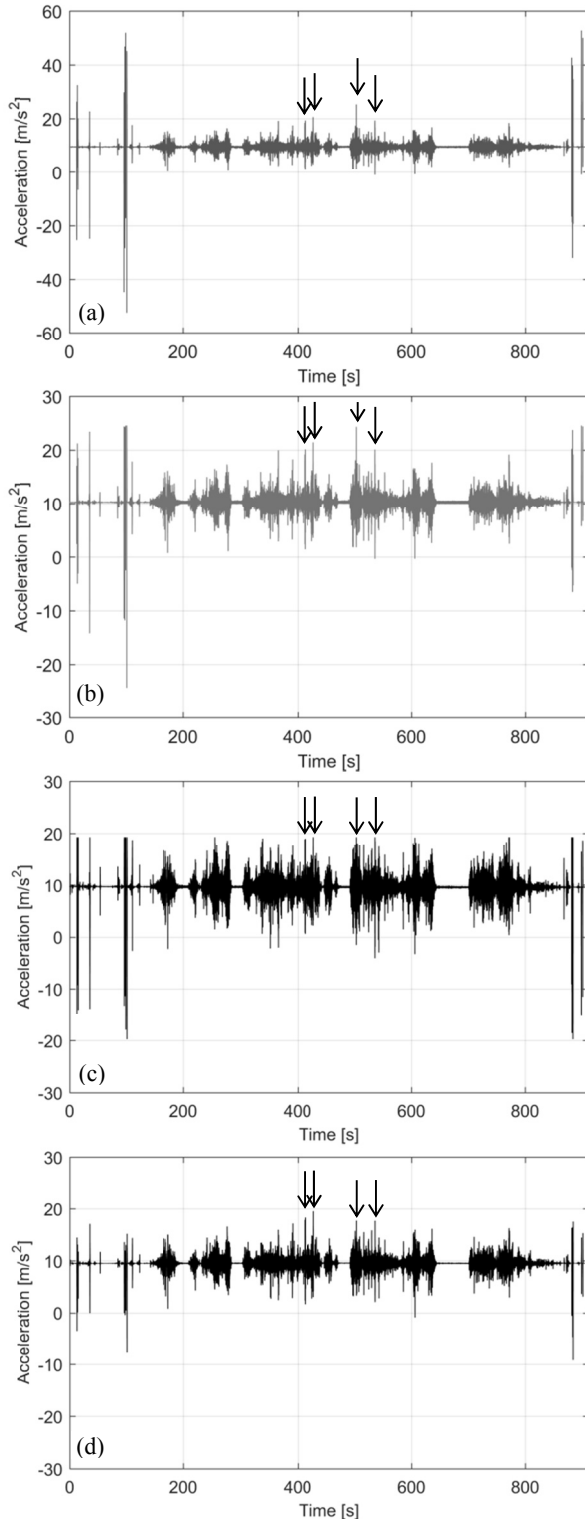


Figure 4. Acceleration measurements for test route 1 (a) 5g uniaxial (b) 2g uniaxial (c) Nexus 5 MPU-6515 (d) S4 K330.

On inspection of video footage, it can be confirmed that these correspond to the three expansion joints on the bridge, indicating that the drive-by monitoring system, at a minimum,

has potential to monitor deterioration of the expansion joint covering and/or the joint itself through analysis of the vehicle's dynamic response. Further analysis of these responses is necessary to investigate the effectiveness of other indirect drive-by monitoring methods and algorithms, including those developed by the authors.

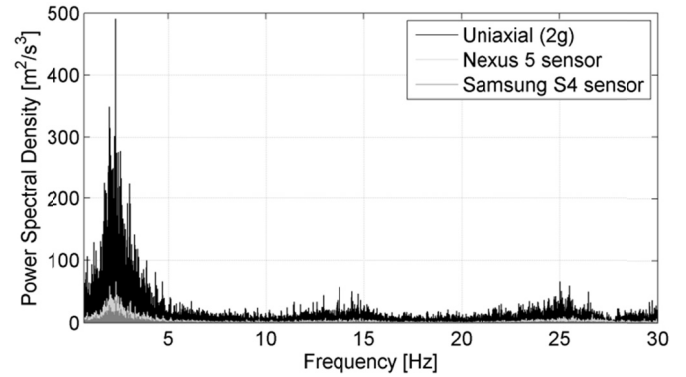


Figure 5. Acceleration spectra for test route 1.

Table 1. Magnitudes in ( $\text{m/s}^2$ ) of peaks exceeding 2g on test route 1.

Accelerometer	Peak 1	Peak 2	Peak 3	Peak 4
5g uniaxial	19.31	20.6	25.31	19.3
2g uniaxial	20.13	21.42	24.31	20.09
Nexus 5 MPU-6515	18.92	19.24	19.24	19.24
S4 K330	18.27	19.5	17.69	17.67

Table 2. Times of peaks exceeding 2g on test route 1.

	Peak 1	Peak 2	Peak 3	Peak 4
Time from start [s]	413	428	504	536
Real time [hh:mm:ss]	15:56:49	15:57:04	15:58:20	15:58:52

### 3.2 GNSS tracking measurements

Figure 9 shows the vehicle location coordinates logged and timestamped during test route 1 by the Leica GS14 smart antenna. The four peaks identified from the acceleration time histories are indicated by white icons having a black dot, highlighting that where video or imagery are unavailable in practice, the location of specific points of interest can be identified via GNSS. These coordinates were logged manually as static points, thus accuracy varied due to the movement of the vehicle. The coordinate quality ranged from 0.01 m in relatively open areas to 8 m in wooded areas. The largest causes of error were trees or wooded areas lining the road which restricted a clear view of the sky for the antenna.

The vehicle position coordinates logged by the Leica GS14 during test route 2 are shown in Figure 10, where icons with black dots indicate two separate bridge crossings. The coordinate quality ranged 0.01 m to 5.7 m, averaging at 0.4 m. A gap in recorded coordinates can be seen at the bottom left of Figure 10; this was caused by a temporary crash of the CS15 controller operating system. This can be overcome by automatically logging raw data to the GS14's internal

memory, rather than manually as in this test. Overall, similar issues affecting accuracy were experienced as for route 1. In particular, at the M1 motorway bridge crossing (see Figure 10 inset), overhanging trees restricted recording of location at the western entrance to the bridge (Figure 7). In addition to raw data logging, this problem can be alleviated for GNSS systems by carrying out testing in winter rather than summer, when trees have shed their foliage. Other possible solutions include inertial navigation systems (INS), which incorporate accelerometers, gyroscopes, magnetometers and GNSS receivers, but an equivalent system for accurate vehicle tracking can be relatively expensive.

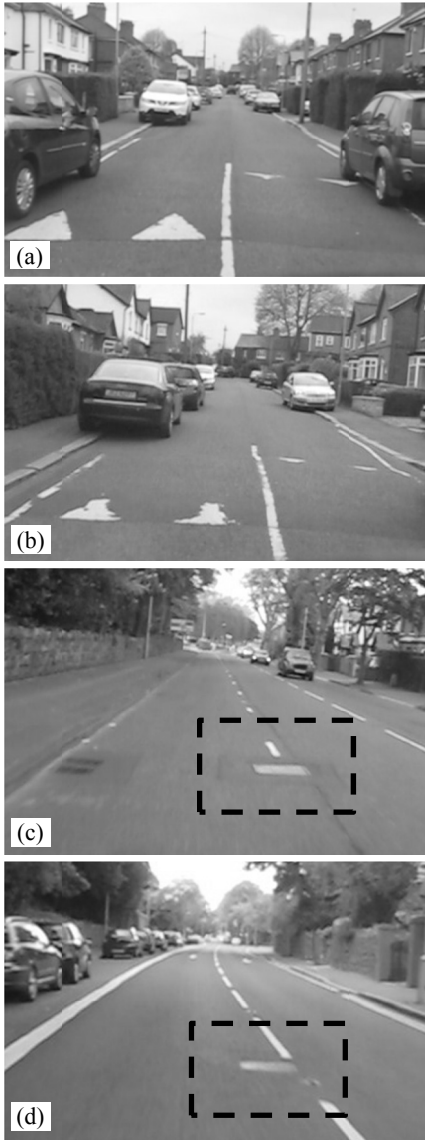


Figure 6. Video screenshots of peak locations for test route 1 (a) Peak 1 (b) Peak 2 (c) Peak 3 (d) Peak 4.

Figure 11 illustrates the vehicle position recorded by GPSEssentials during test route 2. The rapid update of position and accuracy in the region of the M1 bridge crossing is particularly of note – for this application its performance has at least equalled and possibly surpassed the Leica system. Therefore, there is a trade-off between optimum location for each application, unless an external antenna is used for the

smartphone. Despite this, overall it was observed that the smartphone accuracy was sufficient to identify when the vehicle was on the bridge. In terms of post-processing and visualising coordinates, GPSEssentials was very straightforward due to the output of a .kml format file; the Leica system required more user post-processing time to achieve the same output.



Figure 7. West entrance to bridge crossing over M1 motorway on Dunmurry Lane on test route 2.

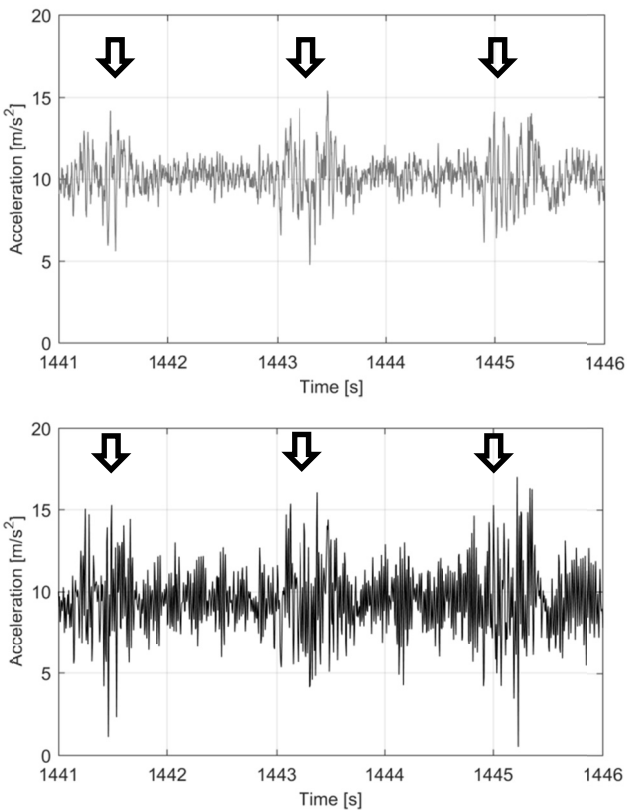


Figure 8. Acceleration measurements on bridge crossing over M1 motorway (a) 2g uniaxial (b) Nexus 5 MPU-6515.

#### 4 CONCLUSIONS

For the drive-by monitoring system, comparing the smartphone sensors versus the wired accelerometers and Leica GS14 smart antenna in term of cost is straightforward; the wired accelerometers and DAQ system cost in the region of €8000 in total, while the Leica GS14 smart antenna system can retail from €18000 - €28000, giving an overall system cost of at least €26000. The equivalent cost of a smartphone is a factor of 100 less than this, giving a clear advantage to smartphone devices in terms of cost savings; 100 vehicles in a

fleet could easily be used as monitoring vehicles for the same instrumentation cost as one specialized instrumented vehicle.

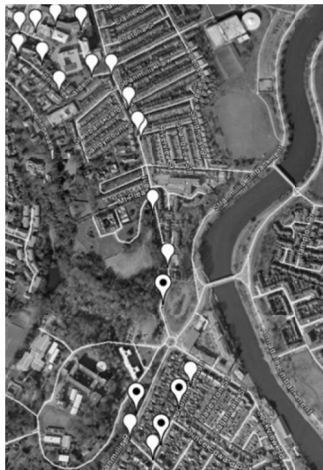


Figure 9. Vehicle position coordinates logged using Leica GS14 for test route 1.



Figure 10. Vehicle position coordinates logged using Leica GS14 for test route 2.

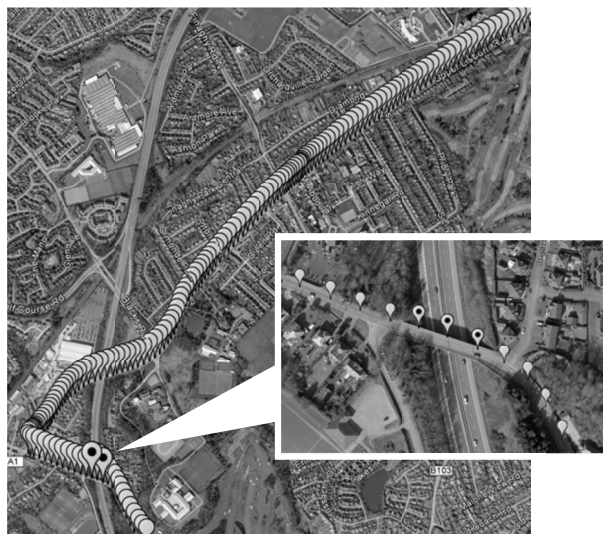


Figure 11. Vehicle position coordinates logged using GPSEssentials smartphone application for test route 2.

The smartphone applications were convenient, easy to use and involved less effort for post-processing vehicle location coordinates, reducing the need for any specialist training. Furthermore, the general level of accuracy illustrated by the smartphone acceleration measurements based on the tested sampling frequency and range indicates that it should be feasible to use these signals for drive-by monitoring approaches, although the levels of noise observed in this investigation must be considered. Further analysis of the acceleration signals and corresponding spectra magnitude is required to establish their suitability for bridge dynamic parameter and damage detection algorithms.

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#### REFERENCES

- [1] Fujino, Y. and Siringoringo, D. M. (2011), 'Bridge monitoring in Japan: the needs and strategies', *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 7:7-8, 597-611.
- [2] Chupanit, P. and Phromsorn, C. (2012), 'The Importance of Bridge Health Monitoring', *International Science Index*, 6: 135-8.
- [3] Rytter, A. (1993), *Vibration based inspection of civil engineering structures*, Aalborg University, Denmark.
- [4] Carden, E.P. and Fanning, P. (2004), 'Vibration based condition monitoring: A review', *Structural Health Monitoring*, 3: 355-77.
- [5] Sayers, M.W. and Karamihas, S.M. (1998), *The little book of profiling*, University of Michigan Transportation Research Institute, UMTRI-96-19.
- [6] Lin, C.W. and Yang, Y.B. (2005), 'Use of a passing vehicle to scan the fundamental bridge frequencies: An experimental verification', *Engineering Structures*, 27: 1865-78.
- [7] Malekjafarian, A., McGetrick, P.J. and O'Brien, E.J. (2015), 'A review of indirect bridge monitoring using passing vehicles', *Shock and Vibration*, Volume 2015, Article ID 286139, <http://dx.doi.org/10.1155/2015/286139>.
- [8] McGetrick, P.J., Kim, C.W., González, A. and O'Brien, E.J. (2013). 'Dynamic axle force and road profile identification using a moving vehicle', *International Journal of Architecture, Engineering and Construction*, 2(1): 1-16.
- [9] Miyamoto, A. and Yabe A. (2012), 'Development of practical health monitoring system for short- and medium-span bridges based on vibration responses of city bus', *Journal of Civil Structural Health Monitoring*, 2: 47-63.
- [10] Stedman II, C. and DeMarco, A. (2007), *Automated GPS Mapping of Road Roughness*, Worcester Polytechnic Institute.
- [11] Poncela, A., de Diego, V., Lorenzana, A., and de Sebastian J. (2011), 'Automatic Portable system for fault detection in the pavement of roads using wireless sensors and GPS', *Proceedings of the 5th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-5)*, 11-15 December 2011, Cancún, Mexico.
- [12] Carrera, F., Guerin, S. and Thorp, B.J. (2013), 'By The People, For The People: The Crowdsourcing Of "Streetbump", An Automatic Pothole Mapping App', *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-4/W1, 29th Urban Data Management Symposium (UDMS 2013)*, 29 – 31 May, 2013, London, United Kingdom.
- [13] Takac, F. and Lienhart, W., (2008), 'SmartRTK: A Novel Method Of Processing Standardised RTCM Network RTK Information For High Precision Positioning', *Proceedings of ENC GNSS 2008*, 22-25 April 2008, Toulouse, France.
- [14] Schollmeyer, M. (2015), *GPS Essentials Manual*, <http://www.gpsessentials.com>.